Report to Congress

Comprehensive Program Plan for High Efficiency Engines and Turbines

March 2002

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Contents

1 Executive Summary

House of Representatives Conference Report No. 234, 107th Congress, 1st Session, 118 (2001), accompanying the Department of the Interior and Related Agencies Appropriations Act for Fiscal Year 2002 (Public Law 107-63), states:

> *The Department [U.S. Department of Energy, DOE] should develop a five-year plan reorienting the turbine program to support vision 21 and focusing on the development of a technology base to increase fuel flexibility (including coal) and efficiency as well as reliability, availability, and maintainability, with low emissions and low life cycle costs. The plan should be submitted to the House and Senate Committees on Appropriations no later than January 15, 2002.*

This Report to Congress responds to the Conference report stated above, and provides a plan reorienting the turbine program to support Vision 21 objectives as noted in the *Vision 21 Technology Roadmap* (2001, National Energy Technology Laboratory). The new program – a reorientation toward high efficiency engines and turbines – follows the successful completion of the Advanced Turbine Systems (ATS) program, detailed in a previous report. The report outlines the DOE National Energy Technology Laboratory (NETL) High Efficiency Engines and Turbines (HEET) Program which focuses on the development of technology to increase turbine power plant fuel flexibility and efficiency as well as reliability, availability, and maintainability, with low emissions and low life-cycle costs. The HEET Program is producing the technology base needed to enable the development of advanced turbines and engine modules for 21st century energy plants. The reoriented Program is integral to and necessary for the success of the DOE Clean Coal Power Initiative, Vision 21, and Distributed Generation programs.

If we are to achieve the National Energy Policy goal of making clean coal competitive in order for it to contribute to a secure, reliable, and affordable source of electricity, the development of high-efficiency engines and turbine technology is key. The turbine manufacturers in a deregulated power generation market have sufficient incentive to meet current demand with their existing line of turbines for gas-based generation. But they have not stepped up to developing fuel-flexible turbines for the future that can run on coal, because this is a long-term high-risk effort that they cannot afford without government assistance. However, the industry has indicated a willingness to partner with the government on this longer-term development effort.

Stakeholders (the power generation industry, energy suppliers, energy consumers, energy service companies, manufacturers and suppliers of gas turbine and engine power generation equipment, the research community, and state energy offices) have expressed concerns about the need for government support to develop high efficiency engines and turbines. DOE has met and conducted workshops with industry and other government agencies. There is strong industry/government consensus that the HEET Program can resolve the technical issues that limit the development of advanced turbines and engines.

The HEET Program is designed to address government and industry needs and priorities, and will result in substantial public benefits from the investment in this technology. It uses science and technology to advance fundamental knowledge and enhance our country's economic competitiveness by building partnerships with the private sector. The program research and development (R&D) portfolio comprises four elements: Advanced Systems Analysis; Simple/Combined Cycle Development; Hybrid Cycle Development; and, Technology Base Development.

The strategy for meeting HEET goals and accomplishing projects within these four elements is to perform R&D in five major technology development areas: Materials; combustion; aero-thermal; instrumentation/condition monitoring; and, design tools. The focus of the program is on technology development and infusion into advanced power systems to achieve the goals of DOE and other government programs, such as the DOE Office of Fossil Energy (FE) Vision 21 and Fuel Cell Programs, and the Clean Coal Power Initiative. Several projects that are already under way will continue under the HEET Program.

The program is managed by the Strategic Center for Natural Gas (SCNG) and coordinated with the Advanced Coal Power Systems Group, both located at NETL. SCNG has sponsored, and continues to sponsor, joint workshops and feasibility studies to coordinate and plan the HEET Program. This coordination with industrial partners, other government agencies, and stakeholders is considered an ongoing task and will continue throughout the Program.

New opportunities have been forged for collaborative R&D with other federal government agencies (U.S. Department of Defense [DoD], and the National Aeronautics and Space Administration [NASA]), state government agencies (for example, the California Energy Commission [CEC]), and the European Union (EU). The Turbine Engine Alliance includes DOE, DoD, and NASA with the FAA soon to join. The Alliance constructively coordinates turbine R&D within the three agencies, identifying technology needs and possible overlapping technology areas.

The American public and our Nation's turbine industry will benefit from the HEET Program through the technology that is created. The Program will yield environmental and savings benefits for the American consumer: Lower energy consumption; fuel cost savings; electricity cost savings; emissions reduction; system reliability; job creation; and, conservation of land and water resources.

2 Introduction

High efficiency engines and turbines will provide clean, efficient power systems to meet the predicted increase in electricity demand over the next 20 years. These advanced systems will also alleviate transmission congestion by encouraging distributed generation and facilitate co-generation. The HEET Program will ensure that goals and objectives of the Clean Coal Power Initiative can be met. The Program will provide the power block modules needed in the Vision 21 and Distributed Generation programs, including hybrid turbine-fuel cell modules. And the Program will help the Nation in its effort to develop technologies to sequester carbon dioxide, a greenhouse gas.

The Past

Since manufacturers introduced gas turbines commercially more than 50 years ago, they have steadily improved turbine efficiency and have reduced emissions. Over the same period, they have also improved their reliability, availability, and maintainability (RAM).

In 1992, DOE initiated the 8-year Advanced Turbine Systems (ATS) Program to push gas turbine performance beyond evolutionary gains. The turbine industry was unwilling to undertake the needed research on its own because of the high risk and high costs involved, and because many of the perceived benefits were long-term public benefits. The Program established aggressive goals to increase turbine efficiency and reduce nitrogen oxides (NO_X) emissions. These aggressive goals were met – 60 percent efficiency for utility-scale, combined-cycle turbines and a 15 percent improvement in efficiency over 1990 levels for industrial-scale turbines. NO_X emissions were reduced to less than 10 parts per million (ppm) – based on 15 percent excess air – for both turbine classes.

ATS technology has been transferred to the private sector for commercial deployment. It represents a major cost and performance enhancement over existing natural gas combined-cycle technology, which is considered today's least-costly, environmentally superior electric-power-generation option. The benefits for Americans are already being felt: (1) offering timely, environmentally sound, and affordable response to the Nation's energy needs; (2) enhancing the Nation's energy security by using natural gas resources in a highly efficient manner; and, (3) providing a cost-effective means to address both national and global environmental concerns by reducing carbon dioxide (CO_2) emissions by 50 percent – providing ultra-low emissions – compared to existing power plants.

The Present

The U.S. energy scenario has changed since the ATS Program was designed. Five current trends in the electric industry are a result of this changed scenario. These trends require new technological capabilities, and leapfrog advances in turbine technologies.

- Gas turbines will continue to dominate the market for new central power production facilities, providing affordable, environmentally friendly electricity worldwide. Turbines may capture over half the market from 2002 to 2010. Central-power stations will meet most of the demand growth. Gas turbine efficiencies will continue to improve: by 2015, we may be seeing 75 percent (Lower Heating Value [LHV]) fuel-to-electric efficiencies for new power plants running on natural gas, and 60 percent (Higher Heating Value [HHV]) efficiencies on gasified solid-fuel systems. The future volatility of gas prices, and recent price spikes over the last 2 years, have forced recognition that fuel diversity is important. New coal-fired power plants are in the planning stages and will play a larger role in fulfilling new capacity needs.

- The use of gasified, solid fuels in turbines is growing. Integrated gasification combined-cycle (IGCC) boosts the advantages of gas turbines and enables the use of potentially lower-cost fuels: coal, biomass, and petroleum coke. Worldwide, syngas production has grown eightfold over the past 25 years; it is poised to grow even more rapidly.

- Pressure is increasing to reduce greenhouse gas emissions through both efficiency improvements and ultimately through carbon sequestration. IGCC systems can be configured to control CO_2 emissions. The fuel gas from a gasifier can be separated into hydrogen and CO_2. The hydrogen can be burned in a hydrogen-burning gas turbine, and the CO_2 can be sequestered (transported and permanently stored).

- The use of distributed energy resources is increasing. Distributed generation operation systems are generally easier to site than large plants. They have the potential for high efficiency, particularly in combined heat and power applications. Distributed energy systems provide an additional tool to maintain grid stability. Distributed generation may capture 5 to 40 percent or more of new capacity additions in the United States by 2020.

- An intelligent infrastructure will increasingly be used. The new energy grid will include smart networks that can communicate in real time. The benefits to the public are reduced costs, minimal emissions, improved reliability, and the ability to provide new customer services.

The Future

As they have since early in this century, coal-fired power plants are expected to remain the key source of electricity in the United States through at least 2020. Coal-fired generation is projected to increase from 1,880 billion kilowatt-hours (kWh) per year in 1999 to 2,350 billion kWh in 2020. Concerns about the environmental impacts of coal plants, their relatively long construction lead times, and the availability of economical natural gas make it unlikely that many new coal plants will be built before 2005. However, nearly 22 gigawatts (GW) of new coal-fired capacity is projected to come on line between 1999 and 2020, accounting for almost 6 percent of all the expected capacity expansion.

Power generators are expected to retire between 10 and 20 percent of their current capacity (based on all fuels) by 2020 because of (1) increased operating costs of aging plants, and (2) tightening emissions regulations. The DOE Energy Information Administration (EIA) predicts that up to 393 GW of new generating capacity will be needed in the United States by 2020 to meet growing demand and to replace retiring units (Energy Information Administration, 2000).

This needed capacity equates to over 1,300 new generating plants of approximately 300 megawatts (MW) per plant. Ninety-two percent of this new capacity is projected to be combined-cycle or combustion turbine technology, including distributed generation capacity, fueled by natural gas or coal.

Combined-cycle technologies offer the potential to generate electricity from coal at higher thermal efficiencies with lower pollutant emissions. The higher thermal efficiencies are possible because in addition to the steam cycle, the hot combustion gases are also expanded through a gas turbine to generate additional power. A modern gas-fired power plant has virtually no sulfur dioxide (SO_2) or mercury emissions, and emits 77 percent less CO_2 than a traditional coal-fired plant. A turbine-based IGCC system is the cleanest, most advanced coal-fueled power-generation option available today.

Actions Taken

A series of road-mapping exercises have been conducted to chart the planned HEET Program as well as to incorporate the HEET Program into the DOE Clean Coal Power Initiative and Vision 21 Program. Workshops have been held with stakeholders to discuss industry perspectives, identify critically needed technologies, outline R&D projects, and plan collaborative efforts. A program plan is being drafted, based on comprehensive analytical review activities that have been coordinated with a broad set of stakeholders. Section 9, Activities to Date, lists past and future HEET planning meetings and workshops. Several projects that are already under way will continue as essential activities in the HEET Program. The projects cover R&D in various research areas including alternative engine concepts, turbine-fuel cell hybrids, coal-fueled industrial gas turbine systems, high-strength materials, sensors/diagnostics, and zero emissions combustion systems. These projects are discussed in more detail in Section 9.

3 National Needs

3.1 National Energy Needs

The increasing worldwide demand for electricity is dominated by fossil-fueled power-generation equipment for new capacity additions, re-powering, and replacement of existing power plants. Electricity suppliers will eventually need power systems that (1) can utilize a variety of fuels and operate flexibly, (2) are reliable, continuously available to supply base-load, intermediate, and peak power, (3) maintain high performance, and (4) use less land and water resources while producing ultra-low levels of pollutants to meet increasingly stringent emissions standards.

Deregulation is forcing all segments of the energy industry to reduce costs. Major program drivers are life-cycle cost reduction and flexible plant design. The HEET Program has been designed to answer national needs: National energy goals, emerging energy challenges, and national legislative mandates.

The HEET Program addresses emerging environmental and electricity reliability issues as well as some of our Nation's critical energy needs:

- Enhancing America's energy security;
- Mitigating the environmental impacts of energy production and use, developing and deploying affordable, clean energy to meet new and increasingly stringent environmental regulations;
- Supporting long-term, high risk research. Under the changing energy industry the emphasis of research and development investment is shifting from long term to short term, rapid payoff technology developments;
- Providing diverse energy technologies for the future, including fuel flexibility to fully utilize U.S. fossil energy resources (coal, natural gas) and alternative fuels (biomass);
- Increasing the competitiveness and reliability of U.S. energy systems; and,
- Enhancing our Nation's competitive position in rapidly growing international power markets.

3.2 National Energy Policy

The HEET Program responds to the five specific goals discussed in the Overview of the *National Energy Policy* report (National Energy Policy Development Group, 2001): (1) modernize conservation; (2) modernize our energy infrastructure; (3) increase our energy supplies; (4) accelerate the protection and improvement of the environment; and, (5) increase our Nation's energy security.

The HEET Program also addresses several specific recommendations listed in the *National Energy Policy* report:

- Encourage increased energy efficiency through combined heat and power (CHP) projects, and promote the use of well-designed CHP and other clean-power generation technologies (Chapter 4, No. 6).

- Establish a national priority for improving energy efficiency, which should be pursued through the combined efforts of industry, consumers, and federal, state, and local governments (Chapter 4, No. 13).

- Continue development of advanced clean coal technologies to increase electricity generation while protecting the environment (Chapter 5, No. 12).

- Extend and expand tax credits for electricity produced using wind and biomass, expand eligible biomass sources and allow a credit for electricity produced from biomass co-fired with coal (Chapter 6, No. 7).

- Develop next-generation technology, including hydrogen, and focus R&D efforts on integrating current programs regarding hydrogen, fuel cells, and distributed energy (Chapter 6, No. 11).

- Expand investment and trade in energy-related goods and services that will enhance the development of new technologies (Chapter 8, No. 5).

- Promote market-based solutions to environmental concerns, and support exports of U.S. clean energy technologies (Chapter 8, No. 24).

- Continue research into global climate change, and identify environmental and cost-effective new technologies that address the issue of global climate change (Chapter 8, No. 25).

3.3 Clean Coal Power Initiative

The DOE Clean Coal Power Initiative (CCPI) is geared to improving the reliability of the U.S. electrical power system by reducing emissions and by increasing U.S. energy security through reliance on our most abundant domestic energy source – coal. In many regions, our expanding 21st century economy is being powered by an out-of-date and undersized electric power system. As the U.S. electric industry transitions to a new and competitive business structure, the demands on the existing fleet of coal-based electric generating facilities are changing. Power plants must operate in a fashion that reduces environmental impact, achieves greater efficiency in operation, remains cost-competitive, and responds quickly to changing customer demand.

The National Energy Policy calls for a 10-year program between industry and government to demonstrate and accelerate emerging coal-based power generation technologies. CCPI projects will demonstrate advanced coal-based technologies that can be applied to improve the performance of existing and new electric power plants, including plants that may be capable of producing some combination of heat, fuels, chemicals, or other useful byproducts. CCPI projects will improve the cost-competitiveness of coal-fired power generation to levels well beyond the capabilities of both existing capacity and technologies already demonstrated.

HEET Program goals and objectives meet the needs of the CCPI: To increase the efficiency of electricity production while reducing environmental impacts associated with air pollutants - CO_2 emissions, water usage, and solid-waste generation. Proposed HEET projects match those targeted in the CCPI: subsystems, components, and modules capable of achieving CCPI objectives. The near-term focus of the CCPI program is on modernizing the existing fleet of aging power plants. Advanced turbines and advanced turbine technologies are already being used to re-power existing plants. The mid- and long-term goals are to develop technologies to significantly increase the efficiency of coal-fired power plants while reducing emission levels to near zero at a competitive cost. Technologies being developed under the HEET Program will be integral to achieving these goals.

3.4 Vision 21 Program

Vision 21 is a strategic alliance – under DOE's leadership – of government-industry-academia collaborative activities associated with the use of fossil fuels, aimed at reducing all harmful emissions to zero, or near-zero, levels. Vision 21 aims to integrate multiple advanced technologies in order to create systems that achieve breakthrough improvements in performance and cost. Vision 21 emphasizes market flexibility, multiple feed-stocks and products, and industrial ecology.

Technologies developed in the HEET Program are a necessary component to produce Vision 21 power modules, including development of fuel-flexible turbines, turbines for large-scale hybrid systems, and sequestration-ready turbines that use hydrogen or combust fossil fuels in oxygen (Figure 1). Turbine technology to be developed in the HEET Program will build upon existing technology developed under the ATS Program and will be extended to match Vision 21 needs by applying expertise in heat transfer, fluid dynamics, combustion sciences, and advanced materials. Performance targets are 60 percent efficiency (higher heating value) for systems based on coal with emissions of NO_X and SO_2 at single digit ppm levels. Some Vision 21 turbines will operate at extremely high combustion temperatures (3,000°F) and will be integrated with fuel-gas cleaning and air separation systems. System dynamics will be a major factor in designing turbines for turbine / fuel cell hybrid systems. Natural gas/oxygen and hydrogen turbines must overcome challenges related to mixing and ultra-high temperature operation. High-temperature steam turbines will also be needed for some Vision 21 applications.

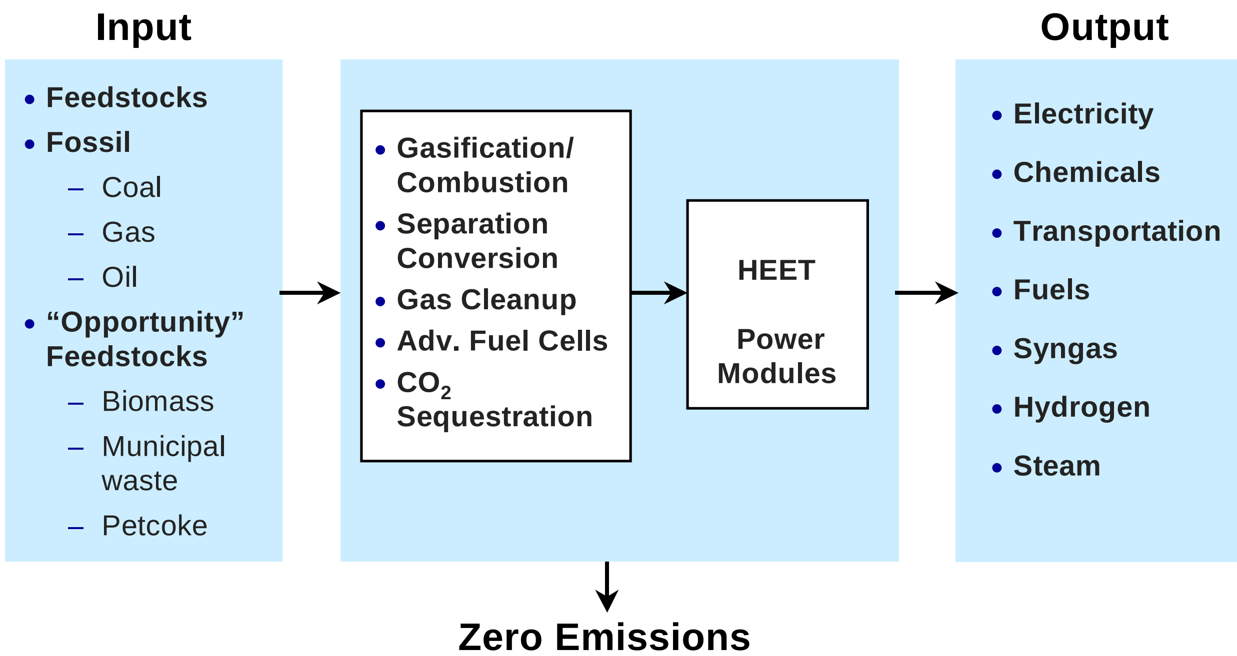


Figure 1. HEET Technology Is Required to Achieve Vision 21 Goals

3.5 Market Needs

Potential domestic markets for high efficiency engines and turbines include base-load power generation, independent and merchant power production, re-powering, industrial power generation (including co-generation), and specialty markets (including distributed power). The key factors that make a technology successful in these markets are:

- Competitive economic performance;
- Commercial guarantees for performance and construction;
- Increased reliability over current plants;
- Fuel-switching capabilities; and
- Acceptable emission levels.

Merchant power plants will be the near-term market growth segment for advanced high-efficiency turbines. Efforts by the Federal Energy Regulatory Commission, and other federal actors, to promote open access transmission and competition in wholesale power markets have led to the recent development of more merchant power plants, and many more will likely be developed in the future.

Distributed power is expected to account for 5 to 40 percent of all load growth in the United States between today and 2020. Combustion turbines and reciprocating engines will continue to dominate distributed power until about 2010 because these technologies continue to improve in cost and size characteristics.

The Energy Information Administration's (EIA) *Annual Energy Outlook 2001* predicts that electricity demand in the commercial and industrial sectors will grow by 2.0 and 1.4 percent per year, respectively, between 1999 and 2020. But the EIA also notes that before building new capacity, utilities are expected to use other options to meet demand growth including maintenance of existing plants, power imports from Canada and Mexico, and purchases from co-generators.

Coal remains the predominant fuel used to produce electricity, but nearly all recently built power plants and almost all of those proposed for the future use natural gas as the primary fuel. Natural-gas-fired facilities are projected to generate about 20 percent of North America's electricity by 2009, compared to just 8 percent in 1991. Most new electricity generation additions over this period will be natural-gas-fired gas-turbine systems.

Concerns about natural gas supply and volatile prices indicate that coal must play a more significant role in meeting increasing electricity demand. Nearly 22 GW of new coal-fired capacity is projected to come on line between 1999 and 2020, accounting for almost 6 percent of all expected capacity expansion. The EIA notes that competition with low-cost gas-turbine-based technologies and the development of more efficient coal gasification systems have compelled vendors to standardize designs for coal-fired plants in an effort to reduce capital and operating costs and maintain a share of the market (*Annual Energy Outlook 2001*).

4 Program Objectives

Specific HEET Program objectives are listed below. These are further explained in Section 5, Technical Issues for High Efficiency Engines and Turbines.

- ***Ultra-High Efficiency.*** HEET systems will have ultra-high efficiencies: 60 percent for coal-based systems (higher heating value [HHV]), and 75 percent for natural-gas-based systems. Turbines developed under the HEET Program will be successfully integrated with fuel cells into hybrid systems for use in distributed generation and Vision 21 power modules.

- ***Environmental Superiority.*** Advanced turbine plants developed under the HEET Program will ultimately have near zero emissions – no carbon, and negligible NO_X, SO_2, and trace contaminants.

- ***Reduced Life-Cycle Cost.*** The life-cycle cost of electricity produced from advanced turbine power plants developed in the HEET Program will be reduced by at least 15 percent compared to current systems.

- ***Fuel Flexibility.*** Advanced high-efficiency engines and turbines developed under the HEET Program will demonstrate fuel and operational flexibility, operating on coal syngas or hydrogen, and have adequate load-following capability.

- ***Improved Electricity Reliability.*** Technology developed under the HEET Program will improve the electricity reliability of the existing and future power-plant infrastructure. These technologies will ensure that coal-fired turbine power plants will have high reliability, availability, and maintainability.

- ***Reduced Water Consumption.*** Technologies developed under the HEET Program will significantly reduce the amount of water needed in power-plant operation.

Leapfrog advances and breakthrough technologies, rather than evolutionary advances, are needed to develop turbine systems that demonstrate ultra-high efficiency, reduced life-cycle cost, environmental superiority, fuel flexibility, improved electricity reliability, and reduced water consumption.

HEET Program objectives directly support the clean coal technology recommendations identified in the *National Energy Policy* report (National Energy Policy Development Group, 2001) and specific objectives noted in the *Vision 21 Technology Roadmap* (National Energy Technology Laboratory, 2001). Achieving the objectives of HEET will be required to attain the goals of the Administration's Clean Coal Power Initiative.

5 Technical Issues

The most important technical issues for developers of high-efficiency engines and turbines are performance (efficiency and output), environmental superiority, fuel flexibility, electricity reliability (RAM), and integration of turbines with fuel cells for hybrid systems. Manufacturers must successfully address these technical issues to produce a viable 21st century HEET power plant. Other technical issues that need to be addressed include reduced life-cycle cost and water consumption.

5.1 Performance

- ***Goal.*** The goal for HEET system efficiency is 60 percent (HHV) for coal-based systems (on a higher heating value basis), and 75 percent (LHV) for natural-gas-based systems. Turbines developed under the HEET Program will be successfully integrated with fuel cells into hybrid systems for use in distributed generation and Vision 21 power modules. Hybrid systems that combine turbines and fuel cells offer the potential for unprecedented efficiencies (in excess of 80 percent).

- ***Current Status.*** Turbine manufacturers have developed natural-gas-fueled engines with improved efficiencies in the DOE ATS Program. Utility-scale efficiencies reach 60 percent in combined-cycle operation and industrial-scale efficiencies show a 15 percent improvement over 1990 levels in simple-cycle operation. All these systems are nearing commercial demonstration. Hybrid systems, which combine two or more power generating technologies into an integrated power generation system, are in the planning stages. The state of the art in turbine-fuel cell hybrid systems is too premature and high risk for industry to do the development on its own.

- ***Technology Improvements To Achieve HEET Program Goals.*** Manufacturers will not achieve the efficiency goals through incremental changes. Significant changes in turbine design are required, particularly in cycle modifications and higher firing temperatures. Integration issues need to be resolved for turbine-fuel cell hybrids. Existing gas turbines will not meet the pressure ratios, mass flows, and other critical operating and performance parameters of high-temperature fuel cells.

  The high capital cost of fuel cell power modules can be improved significantly by incorporating them into hybrid turbine-fuel cell systems. Hybridization leads to a lower cost of electricity. The program goal is $400/kW or less for turbine-fuel cell hybrids as compared to current fuel cell costs of almost a factor of 10 higher.

  Feedstock utilization efficiency (lower heating value basis) will reach 75 percent when producing fuels such as hydrogen or liquid transportation fuels alone from coal. The improved efficiencies will conserve energy through reduced fuel use.

5.2 Environmentally Superior Power Plants

- ***Goal.*** The goal for HEET system environmental superiority is near-zero emissions – no carbon, and negligible NO_X, SO_2, and trace contaminants.

- ***Current Status.*** Turbines developed under the ATS Program achieved NO_X emission reductions to less than 10 ppm (of emission volume based on 15 percent excess air). After-treatment technologies can be used to further reduce nitrogen emissions. However, after-treatment systems involve handling and storage of ammonia, a toxic chemical, and may result in increased ammonia emissions.

- ***Technology Improvements To Achieve HEET Program Goals.*** Higher thermal efficiencies will reduce CO_2 emissions. HEET systems will be made sequestration ready, or will have a relatively simple and inexpensive system for separating nearly pure CO_2 from the gases leaving the system. Reducing CO_2 emissions and sequestering the remaining CO_2 will mitigate concerns over global climate change. These improvements will be validated by testing in small-scale (up to 1 MW) systems during the HEET Program.

  Achieving environmental superiority will require changes in turbine design, since higher turbine firing temperatures tend to increase NO_X emissions. Component development will be needed in a number of areas. One area in particular, combustor design, will require improvements such as hot wall ceramics, catalytic combustion, or staged combustion. Hybridization with a fuel cell will provide additional levels of emission reduction.

5.3 Fuel Flexibility

- ***Goal.*** HEET systems will demonstrate fuel and operational flexibility. They will have the capacity to operate on coal syngas, natural gas, or hydrogen, and have adequate load-following capability.

- ***Current Status.*** Advanced turbines developed under the ATS Program operate on natural gas. Developers plan to include some fuel flexibility, but these changes are only in the design stage.

  Coal is America's most abundant fuel source. The United States has a 250-year supply of coal. New clean coal technologies are showing that air pollution can be reduced and energy efficiency increased by using America's abundant coal supply. Two-thirds of the thermal energy generated in a conventional coal-fired plant in the production of electricity is currently wasted. In IGCC plants on the other hand, coal is gasified instead of being directly burned, and then the gas is combusted in a combined-cycle gas turbine to produce electricity at over 40 percent efficiency – with the potential to achieve over 50 percent efficiency in the future.

- ***Technology Improvements To Achieve HEET Program Goals.*** Gasifiers with improved flexibility, greater reliability, and lower life-cycle cost are being developed under DOE's Vision 21 Program. These advanced gasifiers will be able to process coal-based feedstocks containing up to 30 percent opportunity fuels (e.g., biomass, petcoke). Gasification technology will be combined with gas purification technology to generate electricity with gas turbines and fuel cells in hybrid systems. Under the HEET program, zero emissions combustion systems and turbine hybrids will be developed and integrated with these advanced gasification systems for clean coal power plants. Without these turbine advancements, Vision 21 plants will not operate and perform as directed by the National Energy Policy.

5.4 Electricity Reliability

- ***Goal.*** Technologies developed under the HEET Program will improve the electricity reliability of the existing and future power-plant infrastructure. The reliability of the electric system possesses two components – system security and adequacy. System adequacy refers to having a sufficient supply of generation capacity on hand to maintain security under all but the most extreme circumstances. Maintaining system adequacy involves both the longer-term issue of investment in new generating facilities, but also the ability of those generation facilities to have high availability.

  The electricity reliability goal of the HEET program is to ensure that advanced gas and coal-fired turbine plants have the highest reliability, availability, and maintainability to ensure system adequacy both for the reliability of the transmission grid, and for the benefit of consumers.

- ***Current Status.*** As more and more advanced gas and coal-fired turbine power plants enter the marketplace, the industry focus is shifting from installation to maintenance issues, ensuring adequate management and control of power plant operations and repairs. The industry trend toward increased complexity of advanced turbine power plants makes it an economic imperative that high reliability and availability are the primary emphasis for future operational cost reductions. Rapid growth in demand for electricity has occurred across the U.S. in recent years, causing regional shortages in electricity, which in turn has caused brownouts, blackouts, equipment failures, and very high electricity prices at peak usage periods. The U.S. needs reliable electricity, which means both an adequate transmission system and a sufficient, reliable supply of electric generation capacity.

- ***Technology Improvements To Achieve HEET Program Goals.*** To improve electricity reliability, the RAM of advanced turbine and engine systems need to be improved in order to enhance safe operation, efficient performance, and emissions compliance.

  The gains in efficiency and emissions output reduction, and continued developments in high-temperature materials and improved turbine-blade cooling techniques, have resulted in turbines that can operate at higher performance levels. But these systems require close operational surveillance to protect against failures and to avoid capacity outage. Condition-based monitoring, which supports just-in-time maintenance, will reduce long-term maintenance costs and keep electric prices down for the American public. Advanced condition monitoring systems for power plants must incorporate performance monitoring, mechanical integrity analysis, and component life management.

5.5 Reduced Life-Cycle Cost

- ***Goal.*** The life-cycle cost of electricity generated by advanced turbine power plants developed in the HEET Program will be reduced by at least 15 percent compared to current systems.

- ***Current Status.*** Turbine technology improvements gained in the 1990s are being incorporated into 21st century power systems. However, a technology pipeline is needed to ensure continued advancements.

- ***Technology Improvements To Achieve HEET Program Goals.*** The HEET Program targets a 15 percent reduction in the cost of producing electricity compared to current systems, while meeting increasingly stringent emissions reduction requirements. This reduction can be achieved through increased power output compared to current designs for the same turbine package, condition based maintenance, or through elimination of the downstream cleanup equipment. Integration and technology transfer from defense and aerospace programs will assist in reducing life-cycle cost as technology is pushed to higher and higher performance levels.

5.6 Reduced Water Consumption

- ***Goal.*** Technologies developed under the HEET Program will significantly reduce the need for water in power plant operation.

- ***Current Status.*** Quality and quantity of water is critical to siting and operating power systems. Many regions have compromised water supply systems, particularly in the southwest U.S. But no region can take water resources for granted, and thus any power plant that significantly reduces the amount of water that is typically needed for cooling towers benefits society.

- ***Technology Improvements To Achieve HEET Program Goals.*** Incorporation of advanced natural gas- and steam-powered turbines into power plants significantly reduces the amount of water needed. Wholesale generators of electricity have found that it is much easier to navigate through regulatory hurdles and gain community support when attempting to site a power plant that is considered “dry” – utilizing advanced heat transfer designs for air-cooled condensers and new concepts such as the turbine-fuel cell hybrids that utilize less water per kWh generated. These technologies will be developed under the HEET program.

5.7 Need for Government Funding to Resolve Technical Issues

Since gas turbines were introduced commercially more than 50 years ago, manufacturers have steadily improved performance, emissions abatement, and RAM. Many turbine improvements for the civilian sector occur through military-sponsored R&D programs. The successful DOE-sponsored ATS program provided leapfrog improvements for land-based civilian gas turbines.

The current energy scenario has changed the turbine market and industry's willingness to invest in turbine R&D. Private-sector funding is limited to technological development of incremental upgrades to the basic simple- and combined-cycle systems products being marketed by turbine manufacturers because of:

- The absence of public policy objectives;
- The high risks and high costs associated with developing breakthrough technology; and
- The short-term focus of customers in the deregulated market.

The HEET Program will improve turbine performance significantly beyond what can be expected from industry-sponsored R&D. The HEET Program will ensure that the Clean Coal Power Initiative, Distributed Generation Program, Vision 21 Program, and other federal initiatives have the necessary turbine technology to meet their aggressive goals. Government funding is necessary (1) to meet public policy objectives that require long term, higher risks than industry is capable of undertaking, and (2) to share the risk and accelerate the development of these new systems.

The private sector recognizes that federally supported programs are necessary to significantly and rapidly raise the performance bar for solid fuels. The goal of achieving aggressive, unprecedented, competitive life cycle cost, and continuous electricity reliability, is a prerequisite to developing competitive alternatives to natural gas. However, aggressive, unprecedented technical goals translate to a high level of risk. High-risk programs are difficult for the private sector to support within the global competitive environment. The private sector currently responds to near-term customer needs when selecting technology development options, not long-term issues and priorities identified by the National Energy Policy.

Without government support, the U.S. turbine industry cannot compete with foreign manufacturers who enjoy their government's support. A strategic alliance of U.S. government, American industry, and the Nation's research community will ensure that the U.S. turbine industry maintains its lead in the global marketplace.

6 Program Strategy

The HEET Program strategy is to focus on environmental, performance, life-cycle cost, and reliability issues related to turbine power plants. To find solutions to these issues, technology development is needed in five areas: Materials, combustion and emission reduction, aero-thermal, instrumentation / condition monitoring, and design tools. The strategy is based on significant input from the private sector and other public organizations. This approach offers the best chance of success in achieving the Nation's energy policy goals while yielding environmental benefits and reduced electricity costs for the consumer. The relationship between technical issues, program strategy and program structure is shown in Figure 2 below.

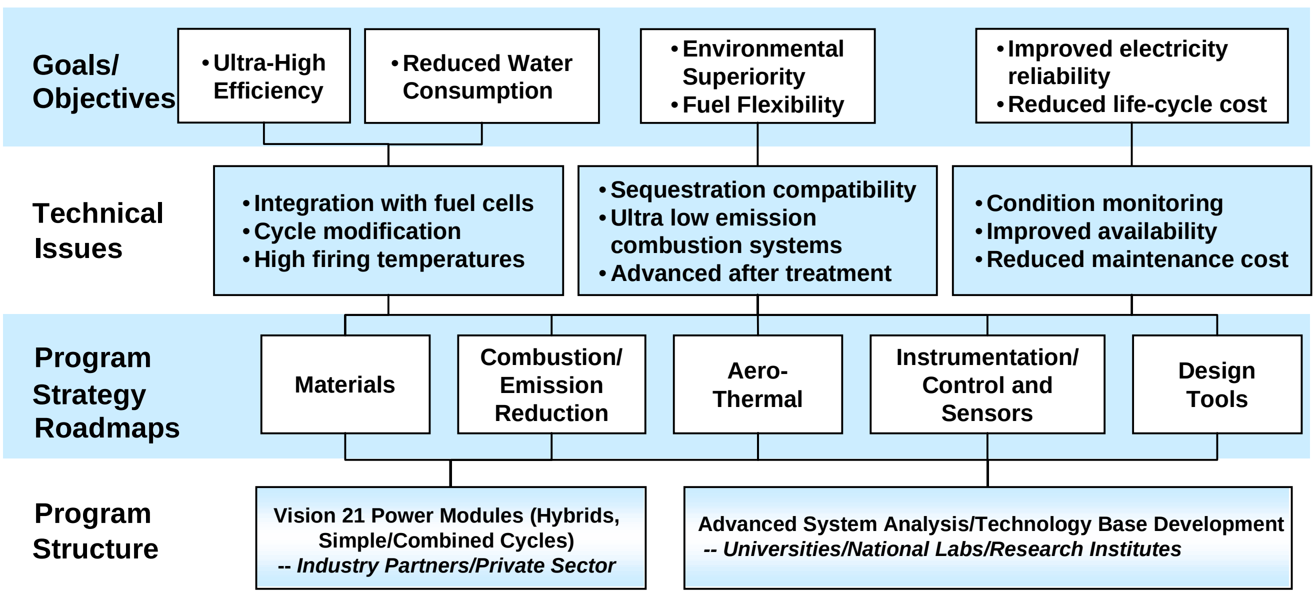


Figure 2. HEET Technology Required to Achieve Vision 21 Goals

Technology roadmaps have been developed with industry and academia in these five development areas. These roadmaps chart technology development pathways that will produce advanced components for Vision 21 power modules. Technologies will be developed and integrated into industrial turbine and hybrid power systems. Component validation and integration will be coordinated with the Clean Coal Power Initiative to promote demonstration of HEET power systems by the private sector.

The five development areas are described below.

6.1 Materials

A roadmap for materials R&D was developed with input from gas turbine developers and researchers. Current land-based gas turbines have incorporated advancements in cooling technology, aerodynamic design, and mechanical innovation. Traditionally, the primary driver for applications other than military aircraft has been to increase fuel efficiency, with emission reduction rapidly rising to prominence in recent years. Both goals require a combination of higher temperature capability in the hot-gas path components and lower requirements for cooling air. A strategic plan to meet these goals, as well as system life assessment, has been developed with stakeholder input. A materials roadmap has been established, and potential benefits have been outlined.

Materials technology is keeping pace with advancements for key components exposed to the hot gas path combustor, transition pieces, and turbine vanes, blades, and disks. Progress is specifically being made in single crystal blades and vanes, wider use of thermal barrier coatings, coatings improvements for oxidation and corrosion protection, and nickel-based alloys for discs. Innovations being studied for future land-based turbines include limited use of structural ceramics, increased use of advanced welding and joining methods, and condition assessment.

Materials R&D in the HEET Program addresses unmet needs and challenges for future land-based systems that will be affected by cycle configuration, firing temperature, fuel type, and duty cycle. Advanced materials developed under the program should enable cycle innovations and turbine design changes that promise 60 percent efficiency for coal-based systems (HHV), and 75 percent for natural-gas-based systems.

Establishing a mechanistic base for models is a research priority. Non-intrusive methods that can monitor the physical state of a turbine component during service are needed for the gas turbine operator. Kinetics of evolutionary processes that lead to failure of hot gas components will be facilitated by smart materials, a term used to include materials or probes that can provide information on the material or coating while in service. The information can then be used with suitable process control to assess remaining life, as well as to regulate the operating conditions.

6.2 Combustion and Emission Reduction

Power generation from fuels generated by coal or biomass gasification could provide a clean energy source for U.S. energy needs. New concepts, such as environmentally superior power plants, will use radically different turbine engine configurations to produce a sequesterable CO_2 stream, thereby virtually eliminating greenhouse gas emissions.

Proposed hybrid turbine-fuel cell systems may achieve unprecedented fuel efficiencies, saving both fuel and reducing CO_2, but these technologies use significantly different operating cycles compared to conventional power plants. In each of these applications, a key technical challenge is designing and controlling the turbine combustion process without compromising reliability or environmental performance.

The focus of combustion and emission reduction research in the HEET Program covers four major topics:

- Improving the simulation of combustion so that the behavior of proposed systems can be evaluated at greatly reduced cost;

- Addressing the problem of combustion stability so that low-emission engines can operate with greater fuel flexibility and reliability;

- Developing sensors and control systems that can improve the reliability of hot-section components in very high efficiency systems or hybrid systems; and

- Investigating novel strategies for combustion that can provide low-emissions on a wide variety of fuels without the cost and environmental tradeoffs of ammonia-based after-treatment.

6.3 Aero-Thermal

To achieve the efficiency goals of the HEET program, advanced turbines will need to operate at higher temperatures and pressures under more severe conditions. Currently, manufacturers utilize air and steam to cool the hot components in turbine power plants. Other components of the turbine power plant, such as air-cooled condensers, are still inefficient and could be improved with advanced heat transfer applications to reduce water consumption. Several barrier issues exist in the area of heat transfer and aerodynamics/mechanics.

The focus of aero-thermal research in the HEET Program covers five major topics:

- Advanced cooling fabrication (surface enhancements);

- Robust gas turbine blade components and increased durability;

- Transpiration hot-gas path cooling;

- Heat transfer for highly loaded aero-thermal designs (wake and shock effects); and

- Compressor cooling at higher pressure ratios, generator cooling and insulation, and advanced cooling for balance of plant (BOP) equipment.

6.4 Instrumentation/Condition Monitoring

Advances in gas turbine technology have raised gas turbine firing temperatures to 2,600°F and pressure ratios to about 30:1, resulting in increased turbine power system efficiencies to greater than 60 percent (LHV) on natural gas fuels, and potentially up to 52 percent (HHV) on coal fuels.

However, the increases have also caused some reductions: Availability has been reduced by as much as 10 percent; nozzle life and first-stage blade life have been reduced to less than 25,000 hours; and, combustor liner life has been reduced to 4,000 hours. Leapfrog technology advances are needed to develop advanced technology that is both able to withstand the higher temperatures and pressures and is reliable.

For the past three years, NETL has been developing dynamic models as part of collaboration with the National Fuel Cell Research Center located at the University of California at Irvine. Dynamic models and control systems need to be developed to design and operate engine/fuel cell hybrid systems. Following a detailed design phase, NETL is constructing an experimental hybrid simulator. This facility will be used (1) for experimental validation of dynamic models, and (2) to provide a test bed for the control systems needed for hybrid systems.

A performance-based condition monitoring approach to improving power plant performance will enable turbine operation at major utility and process plants to be safer, more environmentally friendly, more flexible, more reliable, and more profitable than is possible today.

Condition monitoring research in the HEET Program is aimed at doubling current power plant efficiencies with no reduction in operating and maintenance costs, flexibility of 400 starts per year for gas fueled systems and load change on a daily basis for coal systems, RAM improvement, and operation of coal syngas. Options for reducing operation and maintenance costs include (1) limiting degradation, (2) operating at optimal design conditions while the system is at off-design conditions, (3) improving component life, and (4) increasing the time between major overhauls. RAM improvement studies will include performance-based maintenance and total condition, overhaul, and low-NO_X combustion monitoring. Natural gas will be used as the baseline for fuel flexibility work, with the ultimate goal of high reliability operation on coal fuels. Fuel treatment, fuel tracing and special designs for heavy fuels, and on-line turbine washing will be investigated.

6.5 Design Tools

Benchmark quality data on low-emission turbine combustion flames is a critical need. The HEET Program will address this need using data obtained in national lab and university projects.

Design tools, using advanced numeric simulations, can assess new engine performance while greatly reducing the time needed for development and testing. With continued advances, large-scale computing facilities, as well as distributed computing resources, it may become possible to predict full-engine behavior. This will allow virtual tests of the complex interactions expected to occur in hybrid energy plants. If successful, this could save the cost of building less than optimal prototype plants, because many of the component interactions could be explored before building a physical system.

Because engine manufacturers do not directly profit from software and computing techniques, development of these techniques is often under-funded in the private sector. Emerging high-tech companies that produce software are seldom able to address the huge cost and technical hurdles needed to develop full-engine simulation. For example, the needed experimental data that must accompany simulation development is not readily available to software companies.

To address these barriers, the HEET Program will develop advanced computing methods at national labs, universities, and small businesses. The work will be coordinated with related activities supported by NASA and DoD for flight-engine applications, but will cover the significantly different problems of stationary power. For example, none of the propulsion applications will include hybrid turbine-fuel cells, or adaptations for variable coal or biomass gas.

Perhaps the greatest technical challenge of developing new energy plants is the combustion system. The cost of developing new low-emission turbine combustors usually exceeds tens of millions of dollars, even when using natural gas as the fuel. Adapting a low-emission combustor to a fuel with a different composition, such as coal fuels, may require a similar investment of time and money. The high development cost is one factor that prevents routine engine deployment where low emissions are sought on opportunity fuels such as biomass or hydrogen-rich coal syngas. Likewise, candidate combustor strategies for advanced hybrid power plants can ordinarily be expected to be a high-risk, long-term, capital-intensive venture that industry cannot be expected to undertake on its own. Industry sees no near-term payback from developing new combustors for biomass or syngas. This is slowing efforts to develop innovative, zero-emission power systems, even though the public benefits will be huge.

A reliable, low-cost method to evaluate combustor performance on different fuels could address this dilemma. Progress in numeric simulation of combustion has advanced to the point where basic design features are now routinely assessed using computer simulations. These simulations often provide useful qualitative information about the effect of proposed design changes. However, quantitative accurate prediction of pollutant emissions, and the effects of specific fuel chemistries, are beyond the state of the art in current numeric models. Technical progress on this issue will provide a low-cost method to evaluate the behavior of new fuels in proposed combustor designs.

Technical progress in combustion simulation is linked to available data for model development. A central problem is providing an accurate, computationally tractable representation of key processes in the flame. Data are not available for the type of premixed flames that are used in low-emission turbine combustors. Because turbine combustors operate at high pressures with short residence times and high turbulence levels, creating representative test conditions requires specialized facilities. The required pressures and flow rates are typically found only in commercial turbine development labs. These commercial facilities are often occupied with hardware testing for near-term product development. Experimental data to support models for pre-commercial concepts, such as hydrogen-fueled turbines, is even more difficult to obtain. The research payback is too long and speculative to justify investigation by commercial labs.

7 Program Structure

The HEET Program portfolio consists of four elements: Advanced System Analysis, Simple/Combined Cycle Development, Hybrid Cycle Development, and Technology Base Development. These four elements are described below. The five technology development areas discussed in the previous section are interwoven into the work areas within these program elements.

The Program will be implemented through competitive solicitations and consortia involving industry, national laboratories, and universities. During fiscal year (FY) 2000, several competitive selections were made to evaluate technology needs and benefits of advanced turbine systems. These studies will provide information for program planning, and will define the direction and focus of the R&D portfolio. A follow-on solicitation is planned for FY 2002 to begin implementation of the technology base development element.

Prior to the establishment of the HEET Program, several relevant projects were initiated with teams of industry, academia, and research institutions under FY 2000 broad-based solicitations. These teams are developing gas turbine-fuel cell hybrids and computational tools to (1) improve low-emission combustion design, and (2) test engine concepts such as the Clean Energy Systems (CES) gas generator and the Ramgen engine. Targeted and broad-based solicitations were issued in FY 2001 to continue activities in the five technology development areas, many of which are crosscutting R&D activities. Current projects that will continue as essential activities under the HEET Program are discussed in Section 9, Activities to Date.

7.1 Advanced System Analysis

This element contains one program work area, ***Concept Development***. In this element, systems analysis will be performed to evaluate new, promising concepts such as hydraulic compression or advanced cycles. Information derived from this element will be transferred into the other program elements for further development or assessments.

7.2 Simple/Combined Cycle Development

This element contains five work areas: Syngas Combustion, Durable Materials, Condition Monitoring, Design Tools and Aero-Thermal Technology.

The ***Syngas Combustion*** element will provide the technology to produce clean electricity from coal fuels in advanced clean-coal power systems. Technologies such as catalytic combustion, trapped vortex, or other advanced after-treatment configurations will be developed and validated to reduce emissions from coal-fired turbine plants to near zero levels.

Durable Materials will be developed (1) to withstand ultra-high temperature, corrosive coal-fueled environments; and (2) to reduce the cooling loads on hot turbine parts. This will enable increased firing temperatures and pressures to achieve Vision 21 performance goals.

Condition Monitoring in the HEET Program is aimed at (1) doubling current power plant efficiencies with no increase in operating and maintenance costs, (2) flexibility of 400 starts per year for gas fueled systems and load change on a daily basis for coal systems, (3) RAM improvement, and (4) operation on coal syngas. Options for reducing operation and maintenance costs include (1) limiting degradation, (2) operating at optimal design conditions while the system is at off-design conditions, (3) improving component life, and (4) increasing the time between major overhauls. RAM improvement studies will include performance-based maintenance and total conditioning, overhauling, and low-NO_X combustion monitoring. Technologies developed in this area include high temperature sensors, prognostics, diagnostics, controls systems, and instrumentation hardware.

Aero-Thermal Technology will address advanced cooling, aerodynamic designs, and durability under high loaded conditions. Activities will include new design configurations and testing to ensure that advanced materials and combustion systems are capable of high performance levels. Increased performance of air cooled condensers to reduce water consumption will be achieved.

Design Tools using advanced numeric simulations can assess new engine performance while greatly reducing the time needed for development and testing. With continued advances, large-scale computing facilities as well as distributed computing resources may make it possible to predict full-engine behavior. This will allow virtual tests of the complex interactions expected to occur in hybrid energy plants. If successful, this could save the cost of building less-than-optimal prototype plants, because many of the component interactions could be explored before building a physical system.

7.3 Hybrid Cycle Development

The specific program objective is to achieve the required cost reductions for hybrid systems by combining HEET turbines with Fuel Cell product line resources. Current gas turbines cannot meet the pressure ratios, mass flows, and other critical operating and performance parameters of high-temperature fuel cells. Currently available small-scale fuel cells and turbines will be used to evaluate and resolve some of these integration issues.

The DOE Fuel Cells Program is focusing on the Solid State Energy Conversion Alliance (SECA) with the goal of producing a core solid-state fuel cell module that can be produced at a cost of no more than $400/kW. The aim of the Hybrid Cycle Development element is to produce turbine technology for SECA turbine-fuel cell hybrids, and the ultimate goal is testing a near-commercial-scale multi MW Vision 21 coal-fired hybrid power system.

The ***Hybrid Teams*** work area will consist of one consortium of industry members. The ultimate goal will be to conduct near-commercial-scale demonstrations of Vision 21 hybrid power systems. The industry team will consist of power system developers, sub-system developers, system packagers, and customers. One near-term team will focus on producing a virtual simulation that can visualize and model system performance and manage distributed generation through information technology. Technologies deployed will use heat engines as a major component of the hybrid power system. These heat engines will undoubtedly include new mini gas turbines and other advanced heat engines. The goal for the team will be Vision 21 performance targets.

7.4 Technology Base Development

To support the development and operation of HEET power systems, R&D will be conducted by teams of U.S. government organizations, universities, and DOE national laboratories. These teams will be structured to leverage government and private-sector resources and guided by industrial review boards. Roadmaps for the technology base research and development elements have been prepared with industry, university, and academia. Key R&D technology needs are combustion and low emissions technologies, materials, advanced computing, and condition monitoring. The R&D will support the related private sector activities for development of HEET technology.

8 Program Management

The HEET Program leverages the resources of turbine and engine manufacturers, the electric utility industry, the university community, and government and other private-sector R&D sponsors in pursuit of an important government initiative. Interactions with stakeholders will continue throughout the program. Stakeholder input and assessments will be used to determine the technology development necessary to best serve market needs (discussed in Section 3, National Needs) and for continued program planning.

NETL will implement the program for the DOE Office of Fossil Energy through the Strategic Center for Natural Gas (SCNG). The SCNG is located at NETL and was created in December 1999 as the focal point of all federal activities in natural gas R&D. The SCNG also coordinates natural gas R&D with crosscutting R&D in federal coal programs. NETL has a long-standing program management structure and procedures to conduct government-funded programs.

8.1 Program Coordination

To support the development and operation of HEET systems, R&D will be conducted by teams of U.S. government organizations, industries, universities, and DOE national laboratories. These teams will focus R&D on critical, crosscutting HEET technology barrier issues. Consortia of industry, academia, and government are being established for each of the five strategic technology development areas discussed in Section 6, Program Strategy.

The highly successful consortium of more than 95 universities in 37 states and 8 industry partners developed under the ATS Program is continuing and will be expanded under the HEET Program. In this consortium, industry partners work with universities to develop the technological advances specifically needed by the turbine power industry.

The HEET Program coordination committee includes a sponsor committee and an industry peer review board. The purpose is to keep HEET Program research focused on market and industry needs and public benefits. These partnerships and alliances are being developed both inside and outside of DOE to maximize public benefits. NETL recognizes the importance of developing partnerships with a broad cross section of stakeholders to ensure program success.

Coordination with other federal organizations ensures that HEET systems can serve the needs of all applicable industries, such as refineries, pulp and paper, chemicals, and steel (see Sections 8.3 and 8.4). The coordination also ensures that all funding is leveraged to maximize taxpayer benefits.

The National Association of State Energy Officials (NASEO) is performing a study on potential federal-state cooperation on HEET R&D. Areas for potential collaboration include distributed power applications, university consortium R&D, and technology transfer into advanced turbine-based power plants.

Finally, coordination with other countries (see Section 8.5) is also planned for the HEET Program. Coordination and collaboration with foreign organizations benefits all countries involved as well as consumers.

8.2 Turbine Engine Alliance

DOE, DoD, and NASA have formed the Turbine Engine Alliance. To date, DOE has coordinated six workshops with DoD and NASA and the turbine industry. As a result of these workshops, the turbine industry has proposed several areas for mutual investment among the three agencies. The Turbine Engine Alliance leadership is currently discussing these collaborative opportunities and how all three agencies will support the industry proposals. The FAA is slated to join the alliance in the near future.

The intent of the Alliance is to provide multi-agency collaboration on R&D activities within the federal government that address critical national propulsion and power issues. The goal is to accelerate technology solution applications to resolve national energy, security, and propulsion problems.

8.3 Military and Propulsion Applications

A memorandum of understanding (MOU) has been has been drafted among DOE, DoD, and NASA for propulsion and ground-based power generation. (The Federal Aviation Administration may be added to the MOU in 2002.) The MOU establishes the framework for collaborative work, encourages new agreements, and emphasizes and reinforces current activities among the organizations. DOE is currently awaiting reorganization to be complete within NASA, so that the agencies may proceed with signing the MOU.

This collaboration is currently focusing on core turbine technology that can be used for aviation and ground power, but will be expanded to fuel cells, hybrid systems, and eventually, fuels such as gas-to-liquid synthetic fuels. A cooperative effort on joint turbine R&D for destroyer fleets and future ships is ongoing with the Navy Carderock Division.

A road-mapping exercise was conducted with the Navy, the Coast Guard, and some ship manufacturers. Two power-plant modules were discussed to supply ships with service and propulsion power: One to 5 MW and 10 to 25 MW to supply ships' service power as well as propulsion power. Smaller units, less than 1 MW, have also been targeted for auxiliary power applications.

Turbines, fuel cells, and turbine-fuel cell hybrid systems are ideal to meet future needs for all-electric ships. However, advanced innovative technologies are needed to meet energy requirements and reliability issues.

8.4 European Union

An Agreement for Scientific and Technological Cooperation was initiated in 1997 and signed in May 2001. The Agreement between DOE and the European Community (now the European Union) establishes a framework for collaboration in non-nuclear energy science and technology. Cooperative activities include research, development, and demonstration (RD&D) in fossil energy resources (such as generation of electricity and mitigation of climate change) and new and renewable energy resources (such as fuel cells, the use of hydrogen, and biomass).

The Agreement notes that cooperation can include joint studies, projects, or experiments and activities in partnership with private industry and other non-governmental organizations. A Steering Group has been established that evaluates the status of cooperation, reviews the past year's activities and accomplishments, and reviews planned activities for the coming year.

Talks are ongoing with the European Union to collaborate on joint pre-competitive R&D in turbine related technologies, such as combustion and materials. A collaborative international combustion project on global climate change has been identified that will be supported by the DOE-FE HEET, DOE-Office of Energy Efficiency and Renewable Energy (EE&RE) hydrogen, and EU turbine programs. Several other project opportunities under discussion are outlined in an annex being developed between DOE and the EU for collaborative turbine R&D.

9 Activities to Date

9.1 Program Planning and Roadmaps

A HEET program plan has evolved from comprehensive analytical and review activities beginning in FY 2001. These activities have been coordinated with a broad set of stakeholders. The program focuses on technologies for development of advanced materials, zero emission/fuel flexible combustion, aero/thermal applications, instrumentation/condition monitoring, and design tools.

Stakeholder workshops and program planning meetings have been ongoing since 1995. A list of past and future HEET workshops and planning meetings is shown below.

Stakeholder Workshops and Planning Meetings	Dates
Workshop on Very High Efficiency Fuel Cell/Gas Turbine Power Cycles	October 1995
2nd Workshop on Very High Efficiency Fuel Cell/Gas Turbine Power Cycles	August 1996
Flexible Mid-Size Gas Turbine Program Planning Workshop	March 1997
Flexible Mid-Size Gas Turbine Stakeholder Meeting	October 1997
Regional Stakeholder Workshop, Flexible Mid-Size Gas Turbines for California Deregulated Power Markets	October 1998
Thermal Barrier Coating Winter Workshop	January 1999
Next Generation Turbine Power Systems Strategic Visioning Workshop	February 1999
Aero/Heat Transfer Workshop	February 1999
Combustion Workshop	April 1999
Materials for Land-Based Gas Turbines workshop	August 1999
Instrumentation Issues for Gas Turbine Power Generation Workshop	October 1999
Hybrid Fuel Cell Systems Workshop	November 1999
Materials Program Brainstorming Session	April 2000
Next Generation Turbine Program Stakeholder Forum	June 2000
Combustion VII Workshop	September 2000
Integrated High Performance Turbine Engine Technology Symposium	September 2000
Aero/Heat Transfer Workshop	October 2000
Materials Roadmap Session for Advanced Gas Turbines	October 2000
Open Forum at Power Gen 2000	November 2000
Turbine Power 2000 Workshop	November 2000
International Energy Agency Workshop	April 2001
Panel Discussion on Low-Emission Gas Turbines	June 2001
Panel Discussion on Single Crystal Turbine Blades	June 2001
Advanced Gas Turbine Systems Research Combustion VII Workshop	July/August 2001
Advanced Gas Turbine Systems Research Materials II Workshop	October 2001
Gas Turbine Seminar Program	October 2001
Condition Monitoring Workshop	February 2002
Turbines for Clean Coal Technologies Workshop	April 2002

Roadmaps are being developed with industry to define both competitive and pre-competitive R&D priorities. These roadmaps will be used to implement the program, evaluate and track progress, and measure completion of critical milestones. The roadmaps will also serve as a means for collaboration with other federal agencies, the EU, and state agencies.

9.2 Current Projects Continuing Under the HEET Program

The activities listed below describe currently funded projects that relate to the goals of the HEET program. While it is expected that many of the organizations mentioned below would be participants in the future program, awards will be made competitively. Thus the participants are not guaranteed funds beyond the current commitments of the Department.

9.2.1 Hybrid Cycles

The intent of the hybrids work in the HEET Program is to resolve integration issues, using very small turbines as an expedient method for investigating interface issues. The focus is to develop a suitable larger-size (mini) turbine for use in a SECA turbine-fuel cell hybrid that costs $400/kW or less.

- ***Fuel Cell Energy*** is working with various gas turbine manufactures to develop a hybrid power system that will combine a fuel cell and a gas turbine to generate electricity at ultra-high efficiencies. Integration issues are being resolved by coupling a micro-turbine with a molten carbonate fuel cell. This information will be used to develop an engineering conceptual design of a 40 MW Vision 21 hybrid power module. This project was awarded under the first Vision 21 solicitation in March 2000.

- ***Siemens Westinghouse Power Corp.*** is producing a modular natural gas turbine with extended fuel-use capabilities and the ability to work within a turbine-fuel cell hybrid system.

- ***Honeywell International*** is working on the first stages of development for a new type of planar solid-oxide fuel-cell hybrid system. In the mature version of the technology, the fuel cell will be linked with a micro-turbine to use the energy remaining in the high-temperature exhaust gases exiting the fuel cell.

9.2.2 Simple/Combined Cycle Development

Advanced Concept Studies

Six projects were selected in April 2000 to begin examining innovations that could enhance the efficiency and environmental performance of gas turbines systems greater than 30 MW in output. About half the U.S. demand for gas turbine systems through 2020 is expected to be for industrial turbines suitable for both central and distributed power applications.

The goal is to develop low-cost, zero-emission natural gas/coal fired power plants with efficiencies close to double that of today's fleet; while reducing operations, maintenance, and capital costs by at least 15 percent compared to comparable size units operating today. These turbine systems are planned for use as power modules in Vision 21 energy plants. This will be achieved by integrating the turbines into a simple or combined cycle configuration.

- ***Pratt & Whitney*** will work to develop an intercooled gas turbine with high efficiency without a bottoming cycle and at low capital cost. The study will configure a dry, low emissions combustor, improve cooling and turbine technology, and extend current turbine materials technology.

- ***Rolls-Royce Corporation*** will develop a highly efficient and economically viable power system based on the latest aero-derivative gas turbine and low emissions combustion technologies. The system will incorporate steam injection, recuperation, and intercooling technologies. The study will feature an outline of a plant that could lead to commercialization of the technology.

- ***Siemens Westinghouse Power Corp.*** will work to develop a modular gas turbine with new enabling technologies in a single, low-cost system design that holds worldwide applications. The turbine will be fuel flexible, operating on natural gas and syngas derived from coal or biomass.

- ***GE Power Systems*** will conduct feasibility studies of three broad categories of gas turbines: aero-derivative, heavy duty, and potential hybrids. GE will recommend an engine configuration based on these studies.

Two projects announced in March and June 2000 are developing alternative engine concepts.

- ***Ramgen Power Systems Inc.*** is developing a novel concept that uses ramjets to spin a wheel and generate power. The technology is exciting because it has the potential to significantly lower power-generation initial and maintenance costs, perhaps by as much as 50 percent. The ramgen engine concept accepts waste fuels and very lean fuels such as the unutilized fuel from a fuel cell.

  The goal of the project is to develop a pre-prototype ramjet-like engine that can be a component in Vision 21 energy plants. Use of the engine on opportunity fuels, especially on coalbed methane, is of interest. Ramgen will test a 10- to 15-MW engine, synchronize the engine to the power grid, and initiate analysis and design work for a second engine.

- ***Clean Energy Systems*** is designing and testing a 10-MW high-temperature gas generator that would be used in a zero-emissions power plant. The gas generator, which burns a clean fuel (methane or practically any gaseous fuel or synthetic fuel), is based on rocket engine technology.

The project was selected in the first group under the Vision 21 Program solicitation. NETL believes that the CES approach is a highly innovative approach that has substantial promise for increasing the efficiency and reducing the cost of power generation using coal.

Innovations for Environmentally Superior Power Plants

- ***General Electric Co***. was selected in December 2000 to improve the environmental performance and efficiencies of tomorrow's high-efficiency turbines. In one project, GE will develop a prototype combustor that will reduce smog-causing NO_X emissions by 50 percent or more compared to current lean, premixed gas turbine combustors.

- In a second project, GE will develop a "smart power turbine" sensor and control system. GE will work to develop a suite of novel sensors that will measure combustor flame temperature and hot-gas-component life directly. These sensors and controls would be applicable to both new and existing turbines.

9.2.3 Durable Materials

High-strength materials will be one of the critical requirements for Vision 21 high-tech power plants. Two projects were selected in June 2001 in the third round of the Vision 21 competition. These projects will help improve the strength and durability of tomorrow's metals.

- ***Texas A&M University*** will develop a model that describes how single-crystal turbine blades respond to high temperatures and how defects form and move through turbine blades.

- ***The University of Pittsburgh*** will work to improve the durability of turbine blade coatings, a critical issue in industrial engines because of the greater variety of fuels utilized, many of which contain sulfur, alkali metals, vanadium, or a mixture.

9.2.4 Electricity Reliability

DOE is supporting an effort with private industry to extend the life and improve the operation of advanced turbine power plants. Two of four projects selected in August 2001 will focus on protecting turbine components from erosion; the other two will study ways to improve turbine stability and performance.

- ***Siemens Westinghouse Power Corp.*** will work to improve the life cycle of advanced gas turbines by developing, building, and installing an on-line system to monitor thermal barrier coatings (TBCs). TBCs protect the engine and components against high temperatures.

- ***Solar Turbines Inc.*** will team with CFD Research Corp., Siemens Westinghouse Power Corp., and Los Alamos National Laboratory to produce a laser-stabilization system. The purpose is to reduce combustion vibrations that can lead to turbine instability.

- ***Electric Power Research Institute*** will develop a technology that assesses and manages the life of protective coatings used on natural gas turbine blades and vanes to protect them against high temperatures.

- ***Electric Power Research Institute*** will team with Impact Technologies LLC, Boyle Engineering International, and Carolina Power & Light/Progress Energy to develop a computer program that assesses the total health of natural gas turbines and improves their RAM.

9.2.5 Technology Base Projects

DOE national laboratories are involved in turbine-related R&D. These projects are technology-base development activities. Several projects support R&D on higher performance materials for demanding turbine environments. NETL on-site work is in several technology development areas.

- ***Oak Ridge National Laboratory*** is working on welding and weld repair of single crystal gas-turbine alloys. Oak Ridge will determine the welding behavior of single crystal nickel-based superalloys and develop methodologies to fuse parts without stray grain formation. Currently, large parts that have a single crystal microstructure yield high performance, but require exotic and expensive casting procedures.

- ***Argonne National Laboratory*** is working on two projects that involve structural ceramics. The goal in one project is to develop non-destructive evaluation (NDE) technology for environmental barrier coating and residual life estimation. Argonne will explore the use of NDE techniques to examine accumulated damage in turbine blade environmental barrier coatings. In a second project, Argonne is working on a new approach for evaluating the mechanical reliability of ceramic gas turbine components. Argonne will develop mechanical testing procedures that use miniaturized specimens from ceramic turbine components.

- ***Sandia National Laboratories*** and ***NETL*** are collaborating to investigate the structure of high-pressure pre-mixed flames. The research community developing advanced turbine combustion simulations has repeatedly stated the need for this data. Successful simulation of turbine combustion that accounts for fuel variability could allow turbine developers to market engines that operate on a wide range of fuels.

- ***NETL*** continues R&D on coal syngas combustion and ultra-low emissions. Activity includes the design of a reheater for the CES rocket concept, testing of a trapped vortex combustor under high pressure/temperature conditions, development of a novel flame sensor, and an international collaborative program called “Energy Fuels Simulation Validation.” This is a collaborative partnership with the European Union, NASA, and DOE to develop the most accurate design tools for fossil fuel energy gases and hydrogen.

Clemson University administers the Advanced Gas Turbine Systems Research (AGTSR) consortium. The national network of universities under the AGTSR is mobilizing the scientific talent needed to understand the fundamental mechanisms impeding turbine performance gains and to identify pathways to overcome them. The AGTSR is a university/industry consortium that has grown into a vibrant virtual laboratory with national scope and worldwide recognition. Several projects in HEET Program technology development areas are highlighted below.

- ***Georgia Tech*** (combustion and emissions control) is developing active control approaches to prevent combustion instabilities that have caused excessive noise, vibration damage, and removal of turbines from commercial service for repair. Georgia Tech has demonstrated active control, which has produced a factor of four times reduction in combustor pressure oscillations. Georgia Tech has also been granted two patents and another is in the process, and is working to transfer the technology to four turbine companies.

- ***University of California, Irvine*** (combustion and emissions control) is using several fuels to acquire data for design rules to avoid auto-ignition in lean, premixed, fuel-flexible turbine combustion systems. A knowledge of fuel auto-ignition characteristics as a function of operating parameters is needed for the design of low NO_X combustors. Fuel-air residence times in the premixers of turbine combustors must be sufficiently long for the thorough mixing needed to inhibit NO_X formation, but not so long that premature auto-ignition or damaging flashback into the premixer chambers occurs.

- ***Mississippi State*** and the ***Air Force Institute of Technology*** (aero-thermal) are working to improve aero/cooling design of turbines. The team is providing turbine manufacturers with a database of measured surface roughness and resulting parameters significant to aerodynamic and cooling performance, determined from over 100 parts that had experienced service in turbines. Past analyses of vanes and blades that had operated in turbines have shown that methods established by turbine manufacturers to represent airfoil surface roughness for aerodynamic and heat transfer analyses are not universally appropriate.

- ***University of Connecticut*** (materials) is developing advanced TBC coatings to protect turbine materials from high temperatures and to provide longer lifetimes. Achievement of the project goal of 300ºF higher temperature capability for TBC coatings could increase turbine efficiency, thereby producing a national fuel cost savings of $2.2 billion over 10 years with corresponding substantial reductions in CO_2 emissions.

- ***University of Connecticut*** (materials). Several U.S. gas turbine manufacturers, a coating supplier, and an instrument maker are actively involved in a University of Connecticut project to develop a low cost and portable prototype of a non-destructive inspection (NDI) instrument to be utilized by turbine manufacturers, overhaul facilities, and coating suppliers. NDI methods are needed to alleviate manufacturing quality issues and operational lifetime inconsistencies that have impeded the full implementation of the power and efficiency benefits of TBCs for industrial and utility turbines.

10 Relationship to Other Programs

10.1 DOE Programs

The HEET Program is an integral part of the Clean Coal Power Initiative and the Vision 21 Program, and is indirectly related to several other FE programs:

- ***Clean Coal Power Initiative* –** CCPI projects will demonstrate advanced coal-based technologies that can be applied to improve the performance of existing and new electric power plants. A long-term HEET goal is to integrate candidate HEET systems into zero-emission solid-fueled power plants.

- ***Vision 21 Program* –** Vision 21 aims to integrate multiple advanced technologies associated with the use of fossil fuels. A long-term HEET goal is to integrate candidate HEET systems into fuel-flexible power modules in the Vision 21 Program

- ***Distributed Energy Resources Program* –** Crosscutting technologies developed in the HEET Program will aid in developing mini-power turbines, industrial-scale turbines, gas engines, renewable-hybrid power facilities, and systems controls.

- ***Fuel Cell Program* –** Turbines developed in the HEET Program will be integrated with SECA fuel cells in hybrid power systems.

- ***Renewable Power Programs* –** Fuel-flexible turbines are being developed in the HEET Program that can utilize renewable sources of energy such as biomass.

- ***Hydrogen Program* –** Collaborative research will lead to improved understanding of complex combustion science and technology.

10.2 Other Federal Agencies

DOE is responsible for turbine research for power generation, but other U.S. government agencies funding research on turbines include DoD, the Department of Commerce (DOC), the Environmental Protection Agency (EPA), and NASA.

- DoD is responsible for military propulsion and electric ships.

- DOC develops advanced materials.

- EPA is involved in environmental monitoring.

- NASA is responsible for developing propulsion for civilian aircraft.

In addition to existing programs, technology will be exchanged with these programs. Industry participants and research participants in the HEET Program also typically participate in these other federal programs, establishing effective direct communication links. NETL has established strategic partnerships with all these agencies and will continue working with them to plan mutually beneficial engine and turbine research efforts.

- ***Advanced Technology Programs –*** National Institute for Standards and Testing (NIST) programs to develop and commercialize advanced materials.

- ***Future Ships Programs –*** Naval Sea Systems Command projects to develop the all-electric surface ship of the future.

- ***Integrated High Performance Turbine Engine Technology, and Versatile Affordable Advanced Turbine Engine –*** DoD combined services programs for advanced military propulsion turbine development.

- ***Ultra Efficient Engine Technology Program –*** NASA advanced propulsion program for civilian aircraft proponent development.

10.3 Non-Federal Programs

- ***Public Interest Energy Research –*** CEC research to develop advanced turbines and fuel cell systems for clean, reliable power generation.

- ***European Union Science and Technology Agreement –*** An agreement for scientific and technological collaboration between the European community and DOE.

11 Resource Requirements

This report is based on resources at the level proposed in the FY 2003 budget, and outlines a seven to eight year program. The estimates of cost are based upon information furnished by stakeholders, ATS Program costs, recommendations from workshops and road-mapping exercises, and reports completed by private-sector partners who are currently in the early stages of HEET technology development. These estimates include an assumption of an overall cost-share for the program of 50 percent government and 50 percent private sector. The industry cost-share level would increase from 25 to 50 percent as technology risk is reduced. Supporting R&D cost-share levels would remain at the 25 percent or lower levels because of the high level of risk involved with university and national lab R&D.

Notwithstanding these estimates, nothing in this document should be construed as committing future resources of the government. The President's budget and policy decisions are reviewed annually and all programs are subject to review, since the President's budget must make trade-offs among competing demands throughout the government.

12 Program Performance Indicators and Milestones

The United States will need to rely on fossil fuels for electricity and transportation fuels well into the 21st century. It makes sense to rely on a diverse mix of fossil energy resources rather than on a limited subset of resources. Benefits of the HEET Program match those of the Vision 21 Program:

- ***Removes Environmental Barriers to Fossil Fuel Use –*** smog- and acid-rain-forming pollutants, particulate and hazardous air pollutants, solid waste, and CO_2.
- ***Keeps Energy Costs Affordable –*** wide range of low-cost fossil fuel options available.
- ***Continues U.S. Leadership Role in Clean Energy Technologies –*** promotes export of U.S. fossil energy and environmental technologies, equipment, and services.
- ***Provides the Most Certain Route to Achieving Our Energy, Environmental, and Economic Objectives –*** technology innovation is the best way to address the challenges to our electric power and fuel supply infrastructure.

The HEET Program will result in significant public benefits. Lower energy consumption leads to fuel cost savings, which will mean electricity cost savings for the U.S. consumer. Improved efficiencies will also yield reduced emissions and a cleaner environment for the U.S. consumer. HEET systems offer conservation of natural resources (water and land), especially critical in water-sensitive areas like the southwest U.S. HEET systems will promote system reliability and electric grid stability. Because HEET systems will be fuel flexible, they will expand the options for high-efficiency conversion of domestic fossil energy resources into electric power. They will provide early entry high efficiency technologies for distributed generation at substations and other critical locations in the grid system.

Enabling technologies developed under the HEET Program will benefit and support other missions of the U.S. government, such as enhancing defense capabilities and serving the needs of future military operations. Another large benefit is the creation and maintenance of U.S. jobs directly related to the manufacturing of advanced high efficiency turbines and engines. Increased U.S. jobs are also indirectly related to the low cost and environmental superiority of advanced U.S. HEET systems, which keep U.S. businesses competitive and increase their marketability in the international market.

The U.S. Department of Commerce estimates that over $1 billion in exports equates directly to 20,000 jobs. The U.S. power generation industry currently exports more than $3 billion in power generation systems annually, and about one third of this is turbine systems. According to the 2000 Frost and Sullivan report on North American Gas and Steam Turbine Markets, $8 billion in turbine power plant sales occurred in 1999 in the United States.

When turbine-fuel cell hybrid systems penetrate the U.S. market, these systems will produce less than 1-ppm NO_X emissions and virtually no SO_X emissions. They are at least 70-percent efficient, have a concentrated CO_2 stream, and no particulates even when utilized as electric generation modules in the coal-fired power plants of Vision 21 energy facilities. Estimated benefits for cost of electricity and emission savings are given in Table 1.

TABLE 1. Performance Indicators of the HEET Program

Results	Current	Goal	Benefit
Cost of Electricity (COE) Saved			
Capital Cost	\$600 / KW	\$400 / KW	COE Saved (Gas): \$3.5B/yr
Efficiency (Gas)	40-60% (LHV)	65-75% (LHV)	COE Saved (Coal): \$350M/yr
Efficiency (Coal)	33-37% (HHV)	50-60% (HHV)	
Reliability	< 90%	97%	+1.4% RAM equals 5 additional
Availability	< 90%	95%	run-days per year or \$1B/yr saved
O&M 15% Reduction	0.0015 c/KWh	0.0013 c/KWh	\$300M/yr saved
NO_x Reduction	4.1 lb/MWh	< 0.18 lb/MWh	NO_x Saved (Gas): \$3.2M/yr NO_x saved (Coal): \$5.0M/yr
CO_2 Reduction	1800 lb/MWh	< 90 lb/MWh	CO_2 Saved (Gas): 34M ton/yr CO_2 Saved (Coal): 15M ton/yr
Water Use	1500 gal/MWh	Near Zero	Conservation of Resources

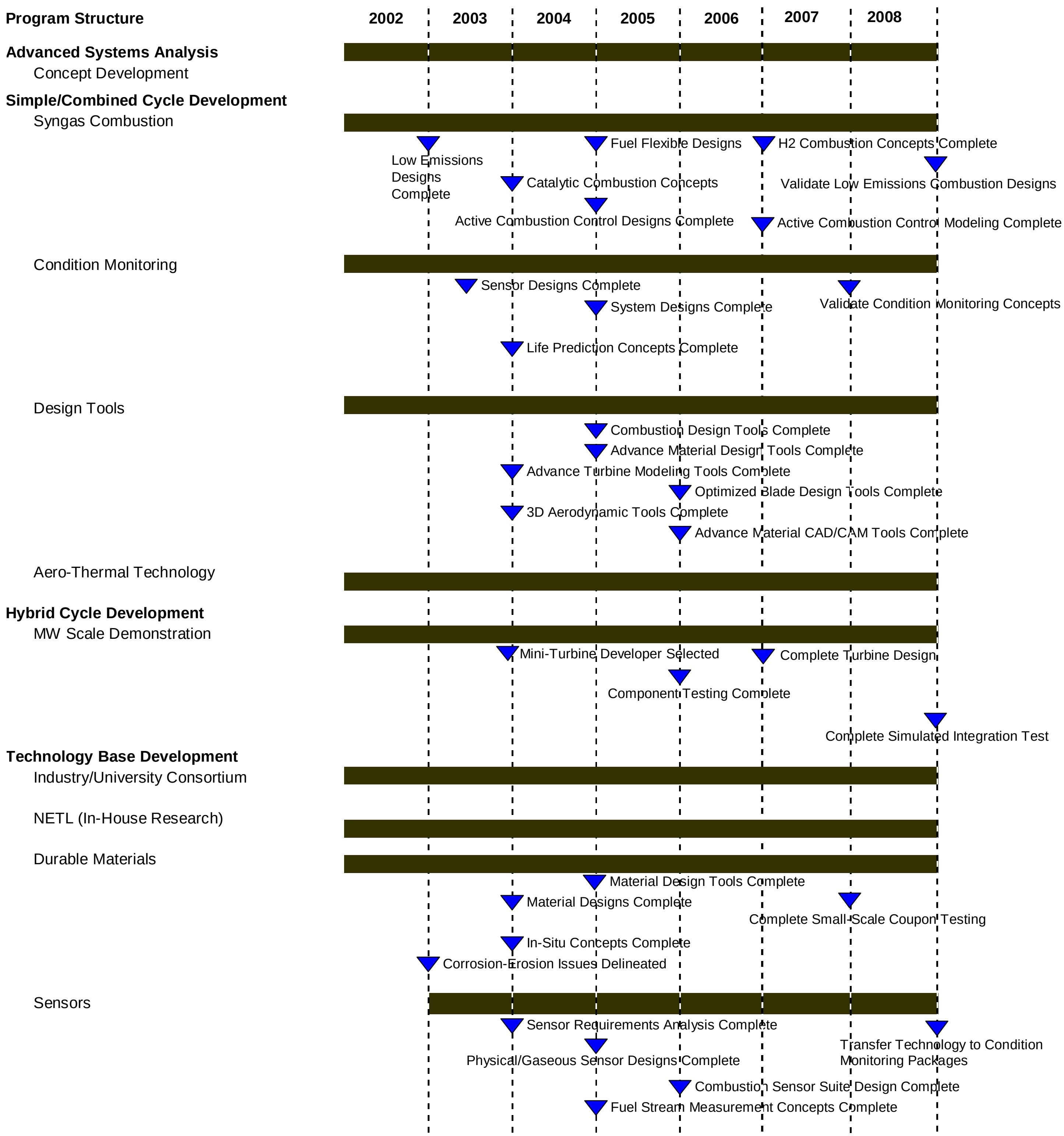
Benefits based on market penetration of advanced technologies to 2020. NO_x savings based on \$420/ton cited by National Research Council report entitled "Energy Research at DOE" (2001).

The HEET Program successfully meets Office of Management and Budget (OMB) investment criteria for a successful program and accountable use of public funds:

- Responds to a presidential priority identified in the National Energy Policy.
- Offers clear public benefits in improved efficiency, reliability, environmental performance, and security.
- Involves technology where private-sector investment is less than optimal.
- Provides a coordinated R&D path that supports federal policy goals.
- Has a comprehensive, complete approach with performance indicators, off ramps, and clear termination points.

The milestone chart given in Table 2 represents the termination points and off ramps for the program.

Table 2. Milestone Chart for the HEET Program



13 Abbreviations

AGTSR	Advanced Gas Turbines Systems Research (Program)
ATS	Advanced Turbine Systems (Program)
BOP	balance of plant
CCPI	Clean Coal Power Initiative
CEC	California Energy Commission
CES	Clean Energy Systems
CHP	combined heat and power
CO_2	carbon dioxide
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EE&RE	(DOE Office of) Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU	European Union
FAA	Federal Aviation Administration
FE	(DOE Office of) Fossil Energy
FY	fiscal year
GW	gigawatt
HEET	High Efficiency Engines and Turbines (Program)
HHV	higher heating value
IGCC	integrated gasification combined-cycle
kWh	kilowatt-hour
MOU	memorandum of understanding
MW	megawatt
NASA	National Aeronautics and Space Administration
NASEO	National Association of State Energy Officials
NDI	non-destructive inspection
NETL	National Energy Technology Laboratory
NIST	National Institute for Standards and Testing
NO_X	nitrogen oxides
OMB	Office of Management and Budget
R&D	research and development
RAM	reliability, availability, and maintainability
SCNG	Strategic Center for Natural Gas
SECA	Solid State Energy Conversion Alliance
SO_2	sulfur dioxide
TBCs	thermal barrier coatings

14 References

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